CHAPTER 4

Soil Tillage for Sustainable Nutrient Management

Carola Pekrun, Hans-Peter Kaul, and Wilhelm Claupein

CONTENTS

4.1 INTRODUCTION

Soil cultivation has a large impact on factors governing plant nutrient dynamics. From practical experience farmers have known for a long time that soil cultivation causes increased mineralization of organic matter. This is particularly obvious when plowing in short-term leys and even more so when plowing in long-term leys or

permanent grassland. The opposite process, accumulation of organic matter and hence nutrients, as a result of reduced or no tillage, has been studied intensively only since the second half of the 20th century, in conjunction with studies on reduced tillage.[1] Short-term leys or facultative grassland has been an important part of rotations for many years and still is important in many farming systems throughout the world. However, the isolated effect of not cultivating the soil cannot be studied in these rotations since growing perennial forage crops not only implies that the soil remains untouched for a number of years but additionally increases soil fertility due to biological nitrogen fixation, accumulation of easily decomposable organic matter, increased uptake of nutrients from deeper soil layers, etc. However, the emerging agrotechnologies of recent decades have contributed fundamentally to improving experimental prospects in this research field. For example, nonselective herbicides paved the way to study the impacts of annual crops on soil nutrient cycles in uncultivated soil without changing rotation. Hence, this means it became possible to study both the effect of soil tillage on nutrient dynamics and the contrasting effect of not cultivating the soil or cultivating it to a reduced depth or intensity.

This chapter starts of by summarizing effects of soil tillage on nutrient pools and flows, as a contribution to understanding nutrient turnover paths in agroecosystems with different tillage. Following this analytical section, examples from field studies will be presented that demonstrate the extent and magnitude of these effects. Average and extreme examples are taken from different parts of the world, with the majority from the temperate zone: the United States and Europe, with a few studies from Australia, New Zealand, South America, and other parts of the world. The tropical and subtropical zones will not be overstressed in this chapter since reports of only a few studies on tillage effects, mostly related to either nutrient mobilization or, more importantly, weed control, are available. In the final part of the chapter, the implications of tillage for nutrient dynamics are discussed with respect to sustainability of farming systems.

4.2 ANALYSIS OF THE IMPLICATIONS OF SOIL TILLAGE FOR NUTRIENT DYNAMICS

To evaluate the effect of soil tillage on nutrient dynamics it is necessary to distinguish between short-term and long-term effects. When tillage is changed on one field from a specific, long-term tillage regime to another, e.g., from conventional tillage to no-tillage, the previously established steady state of the system is disturbed substantially. After the new practice has been adopted and used over a longer period of time the system moves to a new equilibrium. This can be a long-lasting process that often takes decades. The time necessary to reach a new steady state depends on the extent of the change in farming practice. Increasing depth of tillage by several centimeters will require only a few years, whereas converting old, humus-deficient arable land into grassland may require several decades. The system behavior that is observed during this period of adjustment is not necessarily valid in the long term after a new equilibrium has been reached.

4.2.1 Short Time Scale

A single tillage operation affects nutrient dynamics mainly by altering the physical properties of the soil and by incorporating crop residues and other organic material into the soil. The mode of action of the mechanical intervention can be described as:

1. Breaking up the soil with immediate changes in soil porosity and thus aeration, water infiltration, and storage. The exposed surface of soil aggregates is enlarged by destroying large clods while breaking them into smaller ones.
2. Mixing of soil and externally added substances, e.g., crop residues and fertilizers, into the soil resulting in homogenization of the tilled layer.
3. Inversion of soil layers, which affects environmental conditions for microorganisms and other soil organisms within the soil and results in a soil surface free of vegetation or plant residues.

4.2.2 Long Time Scale

When a specific tillage operation is repeated over many years, short-term effects accumulate, thereby building up an additional systems effect. The accumulated effects may be larger than the sum of the single short-term effects. In addition, considerable responses of the soil biota and of crops can be expected. On their own these factors exert qualitative effects on soil nutrient dynamics. After a system with reduced or no tillage has been established, the following factors can be changed in comparison to a system with regular deep-soil inversion:

1. Due to reduced mixing and reduced aeration soil organic matter is likely to accumulate within the upper soil layer. Like grassland, a nutrient-rich layer develops that differs significantly from that below.
2. The lack of disturbance favors soil organisms, in particular burrowing and surface groups, e.g., earthworms and carabid larvae. Earth cracks and former root channels remain intact, and all these factors generate macropores that result in improved water infiltration after heavy rainfall and decreased nutrient losses by runoff and erosion.
3. Due to reduced evaporation, soil water content tends to be higher in reduced tilled soils. As a result, soil temperatures tend to be lower in spring in temperate climates, impairing microbial activity and early growth of crops. In contrast, in areas with low rainfall, higher soil moisture associated with no-till regimes is highly advantageous to crop growth.

4.2.3 Nutrient Pools and Flows Affected by Tillage

Figure 4.1 summarizes the impact of soil tillage on nutrient dynamics using N as an example. In general, the same applies to other nutrients, although the relevance of the individual pools and flows differs.

Three different nutrient pools can be distinguished in the soil system. These include:

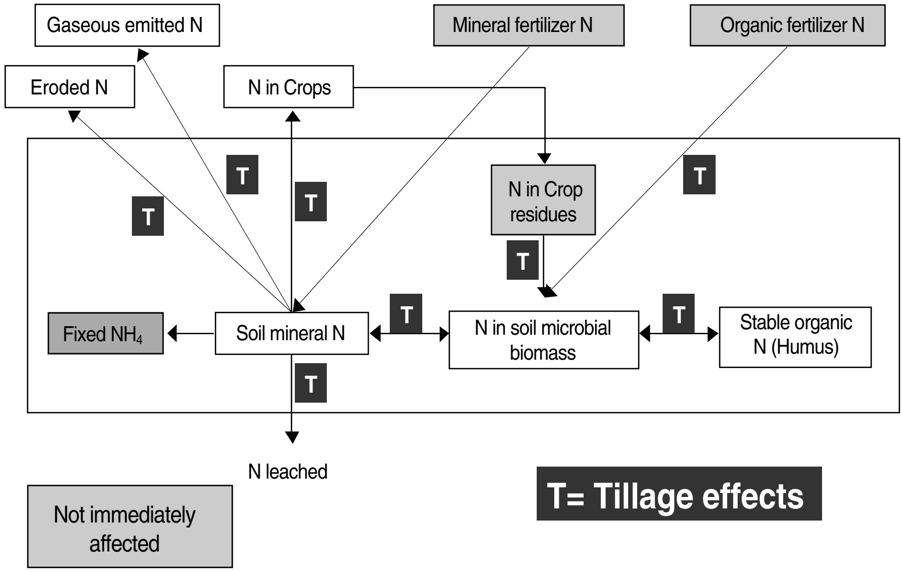


Figure 4.1 Nutrient pools and flows affected by tillage with special reference to N dynamics. T = tillage effects, gray boxes indicate factors that are not immediately affected by tillage.

1. Nutrients in the form of mineral compounds that are easily increased by mineral fertilizers but are removed from the soil in large quantities by growing plants. These nutrients are soluble and subject to losses by leaching, runoff, and gaseous emissions.
2. Nutrients fixed in labile organic substances, i.e., soil microbial biomass and crop residues.
3. Nutrients in stable organic compounds.

Microbial biomass is the most important transient storage pool where organically-bound nutrients from soil humus, crop residues, or organic fertilizers are transformed into mineral nutrients. At the same time, a certain percentage of nutrients is added to the stable organic nutrient pool, and under certain circumstances even mineral nutrients are withdrawn from the soil and immobilized in organic compounds. Some aspects of nutrient dynamics are not accounted for in Figure 4.1, e.g., transport processes of nutrients from the same pool and between different soil layers.

It is obvious that nearly all nutrient flows that represent nutrient transport and transformation processes are affected by tillage. Consequently, the size of most nutrient pools that are distinguishable within the soil and the environment is also affected by tillage. How tillage affects the vertical distribution of nutrients, their mineralization and immobilization, nutrient uptake, and nutrient losses can be highlighted as follows.

4.3 EFFECTS OF SOIL TILLAGE ON NUTRIENT DYNAMICS

4.3.1 Vertical Distribution of Nutrients

Annual plowing results in a more or less homogeneous plow layer. In contrast, tillage operations that do not mix the soil thoroughly, like disking, chiseling, or subsoil loosening, cause an enrichment of soil organic matter and nutrients within the upper few cm of the soil. At the same time, they can result in an impoverishment of lower soil layers.[2–9]

An example for the effects of tillage on the vertical distribution of nutrients is given in Table 4.1. Edwards et al. measured pH, soil organic matter, and seven nutrients in a long-term experiment in Alabama, USA.[5] After 10 years of experimentation a clear differentiation was observed between plots with no tillage (NT) and conventionally-plowed plots (CT). In NT plots, organic matter had accumulated in large quantities in the upper soil layer, which resulted in an overall increase of

Table 4.1 Effect of Cultivation Regime on Distribution of pH, Soil Organic Matter and Double-Acid-Extractable P, K, Ca, Mg, Mn, and Zn after 10 Years of Experimentation in Alabama, USA

Soil Depth (cm)	pH		Organic Matter (g kg $^{-1}$)		P (mg kg $^{-1}$)		K (mg kg $^{-1}$)	
	CT	NT	CT	NT	CT	NT	CT	NT
0–5	5.6	5.5	10.2	18.3	42	78	185	168
5–10	5.7	5.9	10.2	16.4	34	54	120	109
10–20	6.1	6.1	9.6	9.9	32	35	113	76
20–30	5.8	5.8	—	—	22	33	54	57
30–45	5.0	4.9	—	—	6	8	36	43
Mean	5.6	5.6	10.0	14.9	27	42	101	90
LSD (0.05)								
Tillage	n.s.		—		3.1		11.5	
Depth	0.1		0.5		4.9		18.3	
Tillage.x depth	0.1		0.7		3.0		ns	
	Ca (mg kg $^{-1}$)		**Mg (mg kg $^{-1}$)**		**Mn (mg kg $^{-1}$)**		**Zn (mg kg $^{-1}$)**	
	CT	NT	CT	NT	CT	NT	CT	NT
0–5	320	529	63	99	13	20	1.2	1.9
5–10	348	560	61	102	13	18	0.9	1.4
10–20	441	451	78	88	12	13	1.0	1.0
20–30	550	478	105	94	12	15	0.6	0.6
30–45	408	375	78	64	2	7	0.4	0.4
Mean	413	478	77	89	11	15	0.8	1.1
LSD (0.05)								
Tillage	24.8		4.5		1.0		0.1	
Depth	39.2		7.1		1.0		0.1	
Tillage.x depth	55		10.1		2.0		0.2	

Abbreviations: CT = ploughed; NT = no-tillage; LSD (0.05) = least significant difference at P = 0.05; ns = not significant at P = 0.05; — = missing values.

Source: From Edwards et al., 1992, with permission.

Table 4.2 Difference between No-Tillage and Conventional Tillage in Soil pH, Soil Organic Matter, and Nutrients with Respect to the Surface Layer (0–5 cm). Conventional Tillage Consisted of Plowing in all Studies apart from Fanzluebbers and Hons (1996) where Conventional Tillage Consisted of Disking and Chisel Ploughing

Author	Years	pH	Soil Organic Matter	P	K	Ca	Mg	Mn	Zn	Fe	Cu
Edwards et al., 1992	10	=	+	+	–	+	+	+	+	o	=
Follett and Peterson, 1988: Site a	16	=	+	+	+	o	o	=	+	=	+
Follett and Peterson, 1988: Site b	16	–	+	+	+	o	o	=	=	=	+
Franzluebbers and Hons, 1996	9	–	o	+	+	=	=	+	+	–	–
Hargrove et al., 1982	5	=	=	+	=	+	=	=	+	o	=
Iragavarapu and Randall, 1995	6	–	o	+	+	o	o	o	o	o	o
Karlen et al., 1991	11	+	+	+	+	=	=	o	o	o	o
Liebhard, 1993a + b	10	=	=	+	+	o	o	o	o	o	o

Abbreviations: Years = years of experimentation; + = increase in NT compared to CT; – = decrease in NT compared to CT; = no difference between NT and CT; o not studied.

organic matter by 56% compared to CT plots. Available nutrients within the upper 45 cm showed a distinct stratification in the NT plots. Except for K, all other nutrients showed a remarkable enrichment in NT plots as compared to CT plots. Soil pH was not affected by tillage regime.

Similar results have been obtained in many other studies. Tables 4.2 and 4.3 summarize the outcome of studies contrasting no tillage (NT) with conventional tillage (CT) for a period of 5 years or longer. Data from Table 4.2 indicate tillage effects in the top 0–5 cm, whereas Table 4.3 reflects the measured effects below, mostly beyond 10 cm depth. Plowing was the standard technique for CT in all papers quoted except that of Franzluebbers and Hons.[9] These workers considered chisel plowing followed by disks as CT. In most studies, soil pH was affected only slightly or not at all by the tillage regime. Liming of no-till soils is usually sufficient to overcome increasing soil acidity. However, there is a certain risk of pH declines attributed to no-till practices if soil liming is not considered, particularly when N fertilizers are used at high rates, whether organic or mineral. Under these conditions Ca and Mg can be exchanged by nitric acid formed from nitrification of ammonium, resulting in further pH reductions. Under extreme conditions acidification can even result in the setting free of Al ions.[10]

All studies reviewed confirmed that there is an increase in soil organic matter in the topsoil of no-tilled soils. In some studies, the observed increases in topsoil were accompanied by a depletion of soil organic matter in deeper soil layers, while in other studies it remained constant. Thus, NT can result in an altered vertical distribution of soil organic matter or in a net accumulation of soil organic matter in the profile.

Table 4.3 Difference between No-Tillage and Conventional Tillage in Soil pH, Soil Organic Matter, and Nutrients with Respect to Layers below 10 cm. Conventional Tillage Consisted of Plowing in all Studies apart from Fanzluebbers and Hons (1996) where Conventional Tillage Consisted of Disking and Chisel Plowing

Author	Years	pH	Soil Organic Matter	P	K	Ca	Mg	Mn	Zn	Fe	Cu
Edwards et al., 1992	10	=	=	=	=	=	=	+	=	o	=
Follett and Peterson, 1988: Site a	16	=	=	=	=	o	o	–	=	=	=
Follett and Peterson, 1988: Site b	16	=	=	=	=	o	o	=	=	=	=
Franzluebbers and Hons, 1996	9	=	o	+	+	–	=	+	+	+	+
Hargrove et al., 1982	5	–	–	=	=	–	=	=	+	o	=
Iragavarapu and Randall, 1995	6	–	o	–	–	o	o	o	o	o	o
Karlen et al., 1991	11	–	–	–	–	–	–	o	o	o	o
Liebhard, 1993a + b	10	–	+	=	=	o	o	o	o	o	o

Abbreviations: Years = years of experimentation; + = increase in NT compared to CT; – = decrease in NT compared to CT; = no difference between NT and CT; o not studied.

P and K, as relatively immobile nutrients, are usually accumulated in the surface layer of no-till soils. In the lower layers, P and K content can be reduced compared to CT soils or increased. Quite often, no differences are observed in the lower layers between NT and CT. For other nutrients, no general differences were found between NT and CT soils with respect to vertical distribution of nutrients. There is a tendency toward nutrient accumulation in no-till soils; however, this is not always significant.

Since both nutrients and plant roots are concentrated near the surface of no-tilled soils the appropriate soil sampling depth for immobile elements, in particular P and K, should be shallower than for plowed soil.[11,12] The uptake of micronutrients by plants can be significantly lower in no-tillage treatments compared to that in treatments with conventional plowing.[13] Hence, soil analyses of micronutrients (Zn, Cu, Mn) can provide erratic results relevant to the actual nutrient availability for crops. But existing correlations of yields under tillage with average nutrient availability in the top 15 cm of soil apparently work reasonably well for no-tilled soils, too.[14]

4.3.2 Nutrient Mineralization and Immobilization

Mineralization involves the transformation of organically bound nutrients into inorganic compounds. Nutrients can be bound in soil organic matter, i.e., humus, in crop residues, or in organic fertilizers. This applies not only to N but also to P and S.

Table 4.4 The Effect of Position of Crop Residues

	Incorporated	On the Soil Surface
Control (no residues)	105 c	
Vetch	177 a	156 b
Wheat	73 e	77 e
Maize	71 e	75 de
Soybean	73 e	83 d

On nitrogen mineralized (mg $NO_3 - N + NH_4 - N\ kg^{-1}$) in soil samples incubated at 25°C and 60% water filled pore space for 35 days in the laboratory.

Values followed by the same letter are not significantly different $< p < 0.05$.

Source: From Aulakh et al., 1991, with permission.

Mineralization is mediated by microorganisms that use organic carbon and mineralized nutrients for their growth. Nutrients at low concentrations can be withdrawn from the inorganic soil pool for microbial growth, thereby causing immobilization of nutrients. Soil tillage promotes mineralization in two ways: the incorporation of added organic matter, thereby changing its location in the soil profile, and enhancement of aeration, thereby promoting the decomposition of soil organic matter.

When organic material, such as crop residues, weeds, or surface-applied organic fertilizers, are incorporated into the soil, the contact areas between the soil particles and organic materials are increased. Additionally, temperature and moisture in deeper soil tend to be more favorable for decomposing organisms than in soil closer to the surface. Hence, externally added substances are decomposed at higher rates when incorporated into the soil than when lying on the soil surface. This effect of position in the profile has been verified in a number of incubation experiments, although it has been found to be only relatively small.[15–17] Aulakh et al. measured amounts of mineralized nitrogen in incubation experiments, with crop residues of vetch, wheat, maize, and soybean either lying on the soil surface or within the soil. They showed that differences between the two treatments were not large after 35 d (Table 4.4).[18] Cogle et al., on the basis of incubation experiments with ^{14}C-labelled wheat straw, came to similar conclusions.[15] Incorporation of crop residues into soil, compared with leaving them on the soil surface, accelerated organic matter decomposition, but only during the first 15 d.

A lack of differences between the effects of residue incorporation and leaving residues on the surface in incubation studies may be the result of artificial conditions occurring in laboratory studies, e.g., crop residues being dried and ground to a particle size of 5–7 mm or homogeneous soil water content of soil samples in incubation studies. However, under field conditions the position effect has also been found to be relatively small, in particular when studying the decomposition of N-rich material under conditions of adequate moisture availability.[19] Franzluebbers et al. studied the decomposition of canola straw under field conditions for 89–154 d and found that mineralization of plant residues was impeded when the crop residues were lying on the soil surface, but after a period of 5 months differences between incorporating residues and leaving them on the surface were negligible.[20] Considering that,

in nature, large-scale soil disturbance is a rather rare event, these results are not surprising. For instance, in temperate climates, the yearly leaf production of deciduous trees is decomposed by soil organisms without any soil tillage.

Although net mineralization itself may be unaffected by tillage, the composition of decomposer communities can be altered. Schomberg et al. stated that "conventional-tillage systems can be characterized as being bacterial-based food webs with fast rates of litter decomposition, while no-tillage systems support fungal based food webs with greater nutrient retention."[19] Due to a higher ratio of fungal-to-bacterial forms of decomposition with substrates on the soil surface compared to substrates incorporated into the soil, the immobilization of soil mineral N can be higher when applying cereal straw to the surface than when incorporating the straw into the soil.[21] Also, the immobilization of added fertilizer N can be greater under NT than with CT or shallow tillage, due to differences in decomposer community compositions.[22] Increased N retention can be attributed to hyphal bridges allowing fungi to use soil mineral N in parallel with residue C.

Soil tillage is not necessary for decomposition of plant residues. However, apart from incorporating organic materials, tillage also triggers oxidative processes. Increased mineralization following soil cultivation is at least partially attributable to the physical disruption of soil aggregates, resulting in exposure of previously inaccessible soil organic matter to microorganisms and oxygen.[23] Large amounts of soil organic matter have been lost in the North American prairies due to intensive soil cultivation, resulting in immense losses not only of soil organic matter but also of nutrients.[24] Increased rates of mineralization of soil organic matter may also be a major reason for the increased nitrate-N content reported after incorporation of crop residues with high N concentrations.[25–27]

The effects of tillage on net mineralization are very much affected by the time of tillage and environmental conditions prevailing during and after the tillage operations. During periods of cool or dry soil conditions the stimulating effect of tillage on microbial activity is small compared to that during periods of high soil temperature and moderate soil moisture. As a consequence, the timing of tillage can be used as a management tool to control the seasonal pattern of mineralization.[28,29] In an experiment by Francis et al. in New Zealand (Table 4.5), variations in time of plowing a grass–clover pasture had signficant effects on the N dynamics in the soil–plant system.[30] Plowing in May (= winter) instead of March (= autumn) reduced the soil mineral N content in 0–60 cm in June (= winter) from over 100 kg N ha^{-1} down to below 50 kg N ha^{-1}.

Similarly, the intensity of tillage can influence the mineralization processes. After rotovating and plowing in a grass–clover sward in spring, Raupp et al. found peak soil mineral N concentrations under subsequent maize crops or fallow of 117 and 213 kg N ha^{-1}, respectively.[31] Corresponding values after use of a rotary cultivator were 65 and 102 kg N ha^{-1}. Wald studied mineralization as a function of intensity of soil cultivations after breaking a 3-year alfalfa–clover–grass sward.[32] One or two cultivations, using a rototiller followed by plowing, resulted in increased nitrate contents within the upper 60 cm, compared to a single plowing operation before sowing winter wheat, which did not increase nitrate-N content within the soil profile before winter (Figure 4.2).

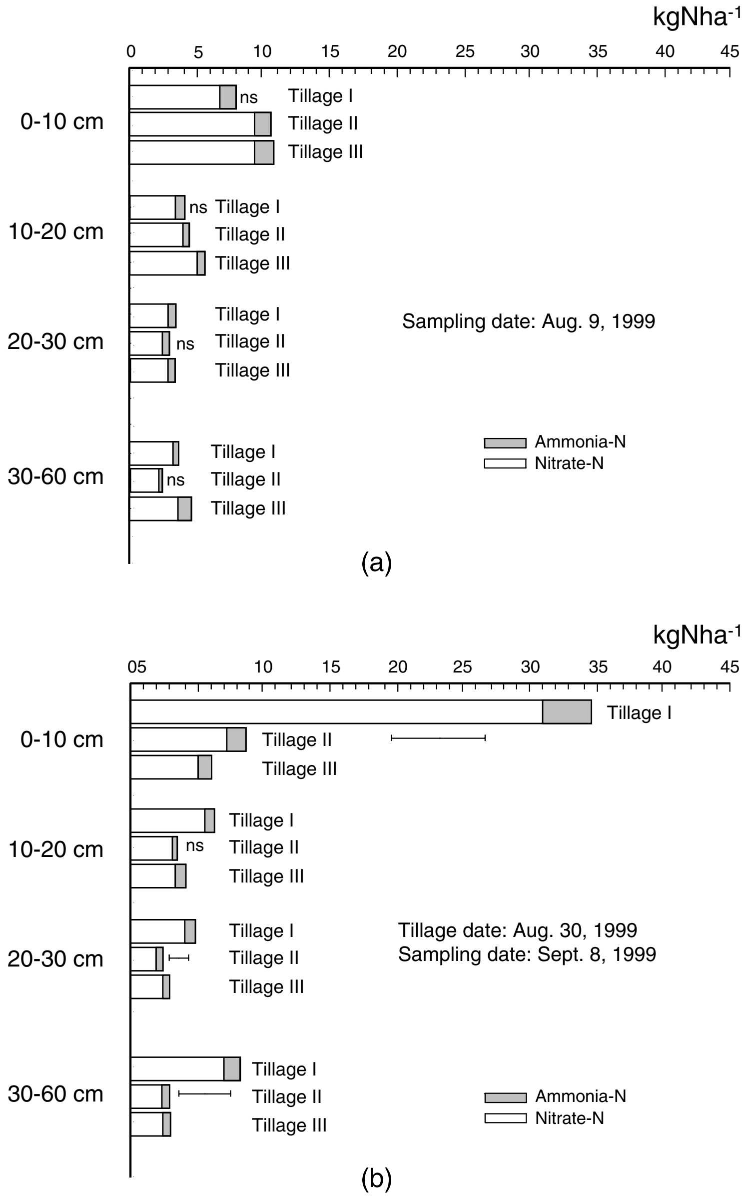
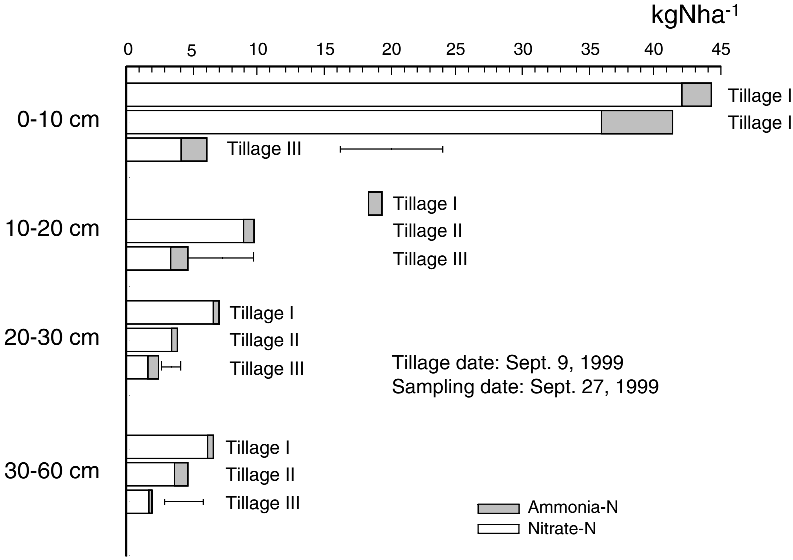


Figure 4.2 Soil mineral N-contents (0–60 cm) as affected by intensity of tillage after breaking up a clover-grass sward. Measurements were taken in August and September 1999 after rotovating once or twice. Treatment I: first tillage 30.8.1999, second tillage 9.9.1999. Treatment II: rotovating only once on 9.9.1999. Treatment III = control, no tillage during August and September 1999.



(c)

Figure 4.2 (*Continued*).

Table 4.5 Soil Mineral N (kg N ha^{-1}) in 0–60 cm in an Experiment Testing the Effect of Timing of Plowing in Temporary Leguminous Pastures in Canterbury, New Zealand

Year	Time of Ploughing	Cover Crop	Soil Mineral N (kg ha^{-1}) June	Soil Mineral N (kg ha^{-1}) September/ October
1991	March	None	131	131
		Greenfed oats	115	17
	May	none	45	131
		Winter wheat	45	102
	October	none	18	10
		s.e.	4.7	6.2
		d.f.	12	12
1992	March	none	107	94
		Greenfed oats	119	54
	May	none	42	105
		Winter wheat*	115	50
	October	none	24	58
		s.e.	13.3	15.1
		d.f.	12	12

*Pasture plowed in March and winter wheat sown in May.

The Leguminous pastures were inverted in March, May, or October. Cover crops were greenfed oats and winter wheat. Measurements of soil mineral N (NO_3^- and NH_4^+) were taken in June (= before winter leaching) and in September/October (= after winter leaching).

Source: From Francis et al., 1995, with permission.

The above experiments were in the context of organic farming and low-input farming in Europe and New Zealand; hence they were under conditions where no or only low amounts of mineral fertilizers were allowed and where, as a consequence, tillage was an important means to control mineralization and thereby the availability of nutrients respective of the amounts of nutrients being lost from the system.

In many areas of the developing world, inorganic fertilizers are not available or are too expensive for farmers to buy. In these regions, the mobilization of nutrients via soil tillage is an important contribution of soil tillage to fertility. Ojeniyi studied nutrient availability and crop growth of maize as affected by soil tillage in Nigeria.[33] He compared 10-cm hoe tillage, row tillage where only a 15-cm wide band along the rows was hoed at 10 cm depth, and no tillage. Zero tillage caused significant decreases in nutrient availability and was therefore seen as not feasible for the conditions prevailing in Nigeria. However, row tillage yielded slightly less than conventional hoe tillage and, being less labor-intensive, was seen as a good compromise for the local farming conditions.

In a transient system gains in soil organic matter and immobilization of nutrients can cause a lag in nutrient supplies.[34] In reduced tilled soils, mineralization rates tend to be slower, and immobilization rates tend to be faster than in conventionally tilled soils.[35–37] As a result, soil organic matter contents tend to increase during a transition period from conventional plowing to reduced tillage,[38] and the content of potentially mineralizable N and P will increase as well.[39–41]

The transition period from an intensive cultivation regime to one of reduced cultivation can last for several years or even decades.[42] During this period it can be sensible to apply extra N fertilizer to account for the reduced mineralization rates under conservation tillage.[43] As can be seen from studies by Ehlers and Claupein in Lower Saxony, Germany, during the period 1972–1976 additions of extra N fertilizer were necessary to account for yield losses in reduced tillage (Figure 4.3).[44] Eight years later, however, no yield differences were observed between reduced-tilled and conventionally-ploughed plots. Apparently, the reduced tilled system had

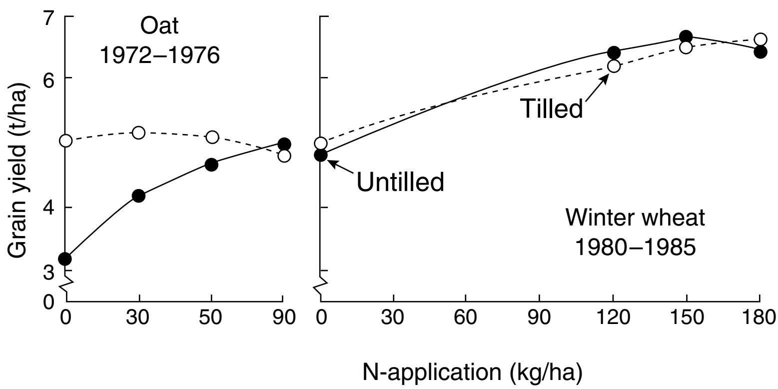


Figure 4.3 Grain yield of oat and winter wheat on a silt loam as affected by tillage and N fertilization in a long-term experiment near Göttingen (Germany). The experiment was started in 1972. (From Ehlers and Claupein, 1994, with permission.)

reached a new state of equilibrium. Soil organic matter had accumulated, other adjustments had taken place, e.g., the improvement of soil structure, so that the efficiency of added N fertilizer did not differ any more between the plowed plots and plots cultivated with reduced intensity and depth. Haugen-Kozyra et al. studying nitrogen partitioning and cycling, under shallow noninversion tillage and no-tillage in Alberta, Canada, came to similar conclusions.[35] In NT plots, added urea appeared to be converted into organic N faster than in conventionally tilled plots.

The rate and degree of organic matter accumulation can differ widely with climate, soil type, quality of applied organic amendments, and general agronomic practices and management. Increases in soil organic matter or EUF-extractable N can be very small, e.g., in soils with large initial amounts of organic matter[45] or in sandy soils.[46,47] Hoffmann et al. studied net N mineralization under sugar beet in plots with conventional and reduced tillage.[48] The experiment was started in 1992, and results were reported for 1993 and 1994, i.e., for 2 years, which should reflect the beginning of the transition process from conventional to reduced tillage. In these experiments, the cultivation regime rather than having a general effect on mineralization rates showed an interactive effect with depth. Whereas at 0- to 10-cm depths mineralization rates were faster with reduced tillage than in conventionally tilled plots, the inverse of this relationship was observed at the 10- to 20-cm depth, and no differences were observed in the 20- to 30-cm layer. Considering the complete layer of 0–30 cm, net N mineralization rates were about equal in both of the two cultivation systems, thus making addition of extra N fertilization unnecessary. A later study confirmed these findings.[49] Soil mineral nitrogen contents that were measured in spring, and after harvest of winter wheat and winter barley, showed no consistent effect of cultivation regimes, indicating a mineralization potential that is lower with reduced than with conventional tillage (Table 4.6). Sieling et al., in a long-term experiment on the effect of tillage and fertilizer regimes in northern Germany, came to similar conclusions.[50] Cultivation regimes hardly affected the soil mineral N content, measured at a depth of 0 to 90 cm depth, four times per year during the first 5 years after shifting to noninversion tillage.

Table 4.6 Soil Mineral N (kg NO_3-N ha^{-1} 0–90 cm) in a Long-Term Experiment on Soil Tillage

	Plow	Deep Noninversion	Shallow Noninversion	LSD $Tukey_{0.05}$
March 1994–1996: in winter wheat	40.4	47.7	45.5	6.3
March 1994–1996: in winter barley	52.3	54.1	55.0	4.3
August 1994–1996: after winter wheat	56.1	48.9	52.3	15.9
July 1994–1996: after winter barley	42.0	42.4	42.1	7.5

Comparing conventional tillage (= plowing to a depth of 30 cm), deep noninversion tillage (= chisel plow down to 30 cm), and shallow noninversion tillage (= cultivations down to 10 cm). Soil samples were taken in spring and after harvest of winter wheat and barley.

Source: From Hoffmann and Koch, 1998, with permission.

Table 4.7 Soil Biochemical Properties in 0–20 cm Soil Depth in a Sorghum-Wheat/Soybean-Rotation and in Continuous Wheat/Soybean under Conventional Tillage (CT) and No-Tillage (NT)

	Sorghum-Wheat/Soybean			Continuous Wheat/Soybean		
	CT		NT	CT		NT
CMIN ($g\ m^{-2}\ d^{-1}$)	2.56	***	3.16	2.89	***	3.78
SMBC ($g\ m^{-2}$)	172	***	197	174	***	220
SRAC ($mg\ C\ g^{-1}\ SMBC\ d^{-1}$)	15.0	**	16.2	16.6	n.s.	17.5
NMIN ($g\ m^{-2}\ d^{-1}$)	0.05	*	0.08	0.06	n.s.	0.08
NMIN ($g\ m^{-2} 18\ d^{-1}$)	4.25	***	6.00	4.99	***	6.69
Inorganic soil N ($g\ m^{-2}$)	4.76	n.s.	4.62	4.46	***	5.59

The experiment was started in 1982, soil samples were taken 1991–1993. CMIN = potential carbon mineralization, SMBC = soil microbial biomass carbon, SRAC = specific respiratory activity of soil microbial biomass carbon, NMIN = net nitrogen mineralization. *, **, *** indicate significance between tillage regimes within a crop sequence at $p < 0.1$, 0.01, and 0.001, respectively.

Source: From Franzluebbers et al., 1996a, with permission.

During the first years after changing to noninversion tillage net mineralization can be slower than with regular ploughing, whereas the opposite effect is possible when the system has been fully established. Table 4.7 shows the results of an experiment in Texas that ran for 10 years. Soil samples were taken from the upper 20 cm,[51] and in almost all parameters that were used to indicate mineralization, the samples from NT plots showed greater activities than samples from CT plots. Hence, lower mineralization rates in no-till systems can be compensated by larger amounts of soil organic matter, after a new steady state has been reached, thus potentially resulting in increased net mineralization compared to conventional ploughing.

Due to enhanced biological activity, in particular with respect to earthworms under no-till,[52] nutrient cycling can be increased in soils under long-term conservation tillage. Helling and Larink found that earthworms significantly enhanced soil mineral N content, possibly as a result of increased microbial activity, in enclosures with earthworms compared with those with no earthworms.[53] Marinissen and de Ruiter studied the contribution of earthworms to carbon and nitrogen cycling.[54] They concluded that earthworms can have a significant effect on N mineralization. From a field experiment on farming systems, including conventional, integrated, and organic farming, they calculated that the direct contribution of earthworms to mineralization was 5 to 8 kg N $ha^{-1}\ a^{-1}$ and an additional indirect contribution of 28 kg N $ha^{-1}\ a^{-1}$.

Mycorrhizal fungi are promoted by reduced tillage.[55,56] As a result, P and N availability for plants can be enhanced by this means in reduced-tilled soils. Bethlenfalvay stated that soil disturbance is perhaps the most direct and drastic among cultural stresses on mycorrhizal development.[57] A number of experiments have shown that there are functional relationships between soil disturbance and impaired colonization of roots by VAM-mycorrhyzae, although reduced tillage intensity did

not always result in increased mycorrhizal populations and better crop yields. In a field experiment on conservation tillage in Canada that had been running for 6 years, McGonigle and Miller reported a positive effect of reduced cultivation on mycorrhizal activity and correspondingly increased P concentrations in maize shoots.[55] However, these effects were observed only during the early growth stages of maize. There were no significant effects on final yield. Entry et al. reported greater root biomass of maize, whether or not infected with mycorrhizae, on a compacted soil under no-tillage compared to conventional tillage.[58] Again, crop yields and plant nutrient concentrations were not affected. In contrast, rhizobium bacteria can be favored by tillage due to better aeration in soil,[59] although in many cases no differences have been found in rhizobial activities between tillage treatments.[60,61]

Irrespective of whether net mineralization is larger or smaller in reduced-tilled soils, nutrient dynamics are very often altered after a management system with reduced tillage has been established. In temperate climates, mineralization is very often slowed down in spring due to greater soil moisture in reduced-tilled soils and correlated slower warming up of the soils. Slow mineralization can result in delayed growth, in particular of spring-sown crops, and in some cases in significant yield reductions.[62]

The organic substances that accumulate as a result of reduced cultivation intensities apparently can very easily be lost again by a single deep cultivation. Plowing land that had reduced cultivation intensity for 20 years resulted in surprisingly rapid decreases in soil organic matter contents, indicating that even after 20 years accumulated humus fractions can be extremely labile.[63]

4.3.3 Nutrient Uptake by the Crop

Crop growth and yields determine the size and form of the nutrient sink and therefore the amount of nutrients that can be taken up by the crop. At the same time, crop growth controls the amount of nutrients that are not taken up by the crop; hence the amount of nutrients that remain in the soil or are lost via leaching, gaseous losses or other pathways. Finally, crop growth directly affects the amount of nutrients being recycled via crop residues.

It is difficult to summarize the overall impact of tillage on crop performance. Many books have been written covering this subject (see, for example, References 64–67), many reviews have been written (see, for example, References 1 and 68–70), and an even larger number of scientific papers deal with the subject. Whereas crop yields have been measured in almost every scientific paper on reduced tillage, nutrient uptake has been studied only in a relatively small number of papers. However, assuming that nutrient concentrations in the crop do not differ systematically between tillage treatments—an assumption that is supported by many papers covering yields and nutrient uptake[8,36,71–75]—yields can be used as an indicator of nutrient uptake.

The effect of tillage on crop yields is very variable. It depends on soil type, climate, and the crop grown. Moreover, it depends to a great extent on the availability of adequate machinery, fertilizers, and pesticides, in particular herbicides, and, last but not least, on the agronomic skills of the farm manager.

Reduced tillage is not feasible on poorly structured soils and soils that are prone to compaction or poor drainage.[70] Under conditions of poor water supply no-tillage

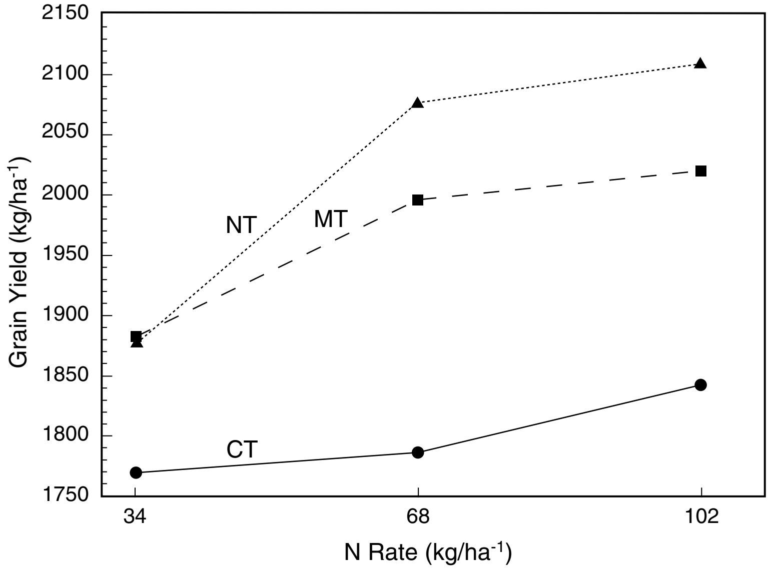


Figure 4.4 Average 12-year grain yields as a function of N fertilization for conventional till (CT), minimum till (MT) and no-till (NT) treatments in a tillage experiment in North Dakota, USA. Tillage x N rate interaction LSD (0.05) = 75 kg ha^{-1}. (From Halvorson et al., 1999b, with permission.)

tends to result in yield benefits due to reduced evaporation from no-till soils.[76–83] Figure 4.4 shows an example from a 12-year study by Halvorson et al. in North Dakota, U.S.[82] In reduced-tilled and no-till plots, yields of winter wheat were significantly higher than yields in conventionally plowed plots. The authors assumed that higher soil moisture content in no-till and reduced-tilled plots was the most likely explanation for these yield differences. The difference in soil moisture need not be large to result in significant yield increases. For instance, Pekrun et al.,[84] measuring soil water content in an experiment on soil tillage in the Marchfeld in eastern Austria, reported that water content in the upper 5 cm was only slightly higher in reduced-tilled plots, in particular in no-tillage plots, resulting in larger yields despite very low plant densities in the no-till plots compared to the plowed plots.[85]

Under conditions of sufficient water supply the situation can be very different. Intermediate forms of reduced tillage, e.g., some sort of noninversion tillage with reduced cultivation intensity and depth, have performed as well in most cases as systems with annual plowing. No-till systems usually resulted in yield reductions and, consequently, lower nutrient uptake by the crop.[69,86] Iragavarapu and Randall studied maize production and N utilization in a long-term experiment on tillage in Minnesota, U.S. (Table 4.8).[8] Grain yields and concurrent N removal by grain were significantly greater under conventional tillage using a plow and disks for primary tillage than in NT plots where maize was directly seeded into the sward. The same trend was oberved for silage yields, although the differences were not significant.

Some crops are better suited for growth with reduced tillage than others. For instance, in temperate climates, winter crops tend to perform better than spring crops.

Table 4.8 Influence of Conventional Tillage

Tillage	Grain Yield ($Mg\ ha^{-1}$)	N Removal by Grain ($kg\ ha^{-1}$)	Silage Yield ($Mg\ ha^{-1}$)	N Removal by Silage ($kg\ ha^{-1}$)
CT	8.64	102.8	14.84	146.0
NT	7.33	83.8	13.22	126.7
CV (%)	11.4	13.8	8.2	14.5
Effect of tillage	**	**	ns	ns

** = means are significantly different with $p < 0.01$.

ns = not significant.

(CT = ploughing 20 cm, discing) and no-tillage (NT) on maize production and N uptake averaged across 11 years. Experiment on a webster clay loam in southern Minnesota, U.S.

Source: From Iragavarapu and Randall 1995, with permission.

Winter wheat is particularly suited for noninversion tillage, whereas sugar beets very often suffer large yield reductions when sown directly into no-till land.[1]

Because there is a potential for nutrient immobilization in the top few cm of no-till soils, subsurface fertilizer placement or banding close to the plant rows can be a sensible means of enhancing the plant availability of nutrients from inorganic fertilizers.[14,87]

Many field experiments have demonstrated that in the first years after changing to reduced tillage, yields were reduced significantly and very variable. However, after a longer time yields stabilized and sometimes also increased, presumably as a result of adaptation processes connected with nutrient dynamics (*cf.* 3.2) and improved soil structure.[88] These gradual improvements may also reflect a learning process of scientists and technicians being involved in the individual projects. Adoption of a new tillage system requires a change not only in the tillage technique itself but also in the entire crop production system.[89–91]

4.3.4 Nutrient Losses

4.3.4.1 Surface Runoff and Erosion

A major aim, and in many cases the most important aim, of reduced tillage is to minimize surface runoff and soil erosion to avoid nutrient and soil losses via these pathways. Nutrient and soil losses are detrimental to yields and the income of the farmer and are a threat to the environment. Soil losses affect the long-term yield potential of arable soils, as shown by Izzaurralde et al. with artificially eroded soils in Canada.[92] Added inorganic N or P fertilizer could not compensate for artificial removal of the upper soil layers. Yields in artificially eroded soils never reached those of natural soils, irrespective of inorganic fertilizer input. This study demonstrated very clearly that topsoil is extremely important for crop growth and that it cannot be replaced by simply increasing inorganic fertilizer rates.

Surface runoff and soil erosion are closely related to land use. In forests or grassland, erosion plays a much smaller role than in arable fields with annual crops.[93,94] With reduced tillage, a soil system is generated that is similar to natural grassland ecosystems with an almost permanent vegetation cover and residue cover

Table 4.9 Effect of Tillage Regime on Runoff of Water after a Longer Period of No Rain

Tillage Regime	Date	Rainfall Events	Rainfall (mm)	Runoff (% Rainfall)
Plow	20 August	thunderstorm	18.1	6.3
Rototiller				0.5
Plow	21–24 August	continuous rainfall	11.1	10.9
Rototiller				0.4
Plow	26 August	thunderstorm	16.5	14.7
Rototiller				0.6

In August 1992 in Lower Saxony, North Germany. Last plow on rototilled plots: 1967. Inclination: 3–5%.

Source: From Ehlers, 1992, with permission.

Table 4.10 Mean Annual Runoff and Loss of Sediment, N, and P as Measured in Watersheds in Texas

	Runoff ($Ml\ ha^{-1}$)	Sediment (kg/ha)	N-losses (kg/ha)			P-losses (kg/ha)		
			soluble	sorbed	total	soluble	sorbed	total
CT	1.3	1575 a	5.9 a	2.2 a	8.1 a	0.7 a	0.8 a	1.5 a
NT	1.3	160 b	3.5 a	0.3 b	3.8 a	0.7 a	0.1 b	0.8 b

Average over 6 years of experimentation. CT = noninversion tillage using a chisle plow, NT = no-tillage. Data with different letters are significantly different at $p < 0.05$.

Source: From Chichester and Richardson, 1992, with permission.

that protects the soil against weathering. It consists of a naturally compact soil with high aggregate stability and a large number of continuous macropores due to soil cracks and root channels remaining intact and to an active soil fauna that "cultivates" the soil without any human inversion. All these factors together result in reduced surface runoff and erosion, as shown in the following examples.

Table 4.9 summarizes measurements of runoff from experiments in Lower Saxony in northern Germany. Ehlers studied runoff after heavy rainfall in August 1992.[95] Whereas in the rototilled plots less than 1% of rainfall was lost via runoff, 6–15% was lost from plowed plots. Lower amounts of surface runoff tend to result in reduced sediment losses.[96] Sometimes, however, there are no differences between tillage regimes with respect to surface runoff and erosion.[97] In other situations, nutrient losses via surface runoff were similar, although nutrient losses via sediments were higher in conventionally tilled soils, as in the study summarized in Table 4.10, which was done in Texas, USA.[98,99] It is also possible that the nutrient concentrations in eroded soil material from no-till soils are higher than from conventionally tilled soils. This can be due to nutrient stratification, which is of particular relevance for P and also may be due to leaching from surface-crop residues.[99]

There have been many attempts to model surface runoff and erosion to assess the long-term effects of erosion on productivity of cropland. Phillips et al. simulated soil and nutrient losses in no-till and conventionally tilled fields for 100 Illinois cropland sites over a period of 100 years using the model *Erosion Productivity Impact*

Calculator (EPIC).[100] Their calculated erosion rates were clearly affected by tillage. Whereas for no-till soils erosion rates were assumed to be 2 t ha^{-1} a^{-1}, simulated erosion rates amounted to almost 10 t ha^{-1} a^{-1} in conventionally tilled plots. Tillage had little effect, however, on overall N and P losses, which were modeled as well.

Reductions of surface runoff and soil erosion can be achieved not only by conservation tillage. Significant reductions can also be a result of contour cultivation instead of cultivation up- and downslopes, as shown by Catt et al. or Foerster and Milne-Home.[101,102] Other options have also been tested in field experiments. Ulén, for instance, studied the effects of autumn plowing vs. spring plowing on P losses via surface runoff in southwest Sweden.[103] However, differences between the two tested treatments were small and inconsistent.

Shallow tillage or no-tillage is not necessarily the best option for minimizing surface runoff and erosion in every site. Studies in Egypt showed that manual tillage down to a depth of 30 cm using an axe for tillage resulted in higher crop yields and lower soil and nutrient losses than chisel plowing down to a depth of 5 cm or 15 cm.[104]

4.3.4.2 Leaching

Leaching can occur to a greater or lesser degree in reduced-tilled soils compared to that in conventionally tilled soils. Very often leaching is not at all affected by tillage regimes. There is a tendency towards lower nitrate content in the soil profile and therefore less nitrate leaching in reduced-tilled soils.[99,105–110] However, leaching is affected very much by the interactions between soil nitrate content and the rates and timing of soil water movement. In reduced-tilled soils, leaching can also be increased.[108,109,111,112] This applies in particular to areas where leaching is a rare event due to little downward movement of water. Increased soil moisture content in conjunction with a larger proportion of continuous macropores can result in an augmentation of leaching losses. Moreover, when shortly after application of mineral fertilizers heavy rainfall occurs, inorganic fertilizer nutrients dissolved in percolating water can be transported into layers below the root zone and into the groundwater. However, continuous macropores do not always result in increased nutrient leaching. Mineral N concentrations tend to be lower in water flowing through macropores than in water within the soil matrix. Macropore flow passes too rapidly downwards to exchange soluble compounds with the soil matrix.[113,114] Additionally, increased nutrient leaching can be due to poor crop growth and related high concentrations of nutrients in the soil solution. Thus, whether leaching is increased or decreased by reduced tillage depends on several factors. Sometimes the differences between the two systems are large, but in most cases they were small or insignificant.[115–117]

Table 4.11 summarizes the results of an experiment conducted near Hannover in North Germany by Stützel and Kage.[110] The tillage regime and N fertilizer rate were tested for effects on nutrient transport. Soil mineral N content were measured in summer after a harvest of field beans and again in the following spring. These and other data were fed into a model named HUME[118] to simulate N dynamics. Model calculations of mineralized and leached nitrogen are summarized in the two right columns of Table 4.11. Tillage had no consistent effect on soil mineral N values measured in summer but were increased in one instance, decreased in another, and

Table 4.11 Soil Mineral N-Contents (SMN)

Year	Tillage	N-fertilizer	Measured Data		Model Calculations	
			SMN in summer (kg N ha^{-1})	SMN in spring (kg N ha^{-1})	SMN in spring (kg N ha^{-1})	Nitrogen leached (kg N ha^{-1})
1994/1995	Moldboard	full	52.4	25.0	26	75
		reduced	55.0	19.3	18	67
	Chisel	full	48.6	18.9	18	65
		reduced	48.6	19.1	17	63
1995/1996	Moldboard	full	37.5	79.1	79	0
		reduced	23.5	69.9	58	0
	Chisel	full	34.8	59.3	58	0
		reduced	38.6	82.0	78	0
1996/1997	Moldboard	full	125.2	68.3	65	127
		reduced	59.1	73.2	71	67
	Chisel	full	92.6	64.5	66	89
		reduced	49.9	56.1	57	55
	SED 1994/95		9.90	3.25		
	SED 1995/96		3.58	11.70		
	SED 1996/97		14.31	13.55		

Measured in summer after harvest of faba beans and in the following spring and calculated values for SMN in spring and N leaching over winter. Modeling on the basis of field measurements in an experiment near Hannover in North Germany with the modeling system HUME by Kage and Stützel (1999).

Source: From Stützel and Kage, 1998, with permission.

not affected by tillage in the remaining four comparisons between chisel and moldboard plow treatments. Soil mineral N content, measured in spring, were significantly less in chisel-plowed plots in three out of the six comparisons and increased in one. Simulated nitrogen leaching rates showed more consistency. They were always lower or equal under noninversion tillage. The differences accounted for values between 4 and 38 kg N ha^{-1}. Hence, in this study, there appeared to be a small but consistent decrease in nitrate leaching by using a chisel plow instead of a moldboard plow for primary tillage.

Figure 4.5 provides an example of a significant increase in N leaching from no-tillage plots. Measurements of soil mineral N are presented that were taken from groundwater samples of watersheds in Oklahoma, USA.[112] All three watersheds—E 1, E 7, and E 8—were in native grassland until 1978. In 1979, watersheds E 7 and E 8 were transferred into arable use using conventional noninversion tillage (sweeps and disks). From 1984 onwards a no-tillage regime was established in E 7. Results are given from 1984 onwards, for the period when no tillage had been started in watershed E 7. It is obvious that in this watershed, nitrate leaching was significantly more than in the two other watersheds. Two factors were assumed to be responsible for the differences between no-tillage and conventional tillage in these studies. With no-tillage, soil water contents were 25% greater than in the other two watersheds. Additionally, crop yields decreased by 33%. As a consequence, nutrient uptake by wheat was significantly less, and more soil mineral N remained in the soil profile.

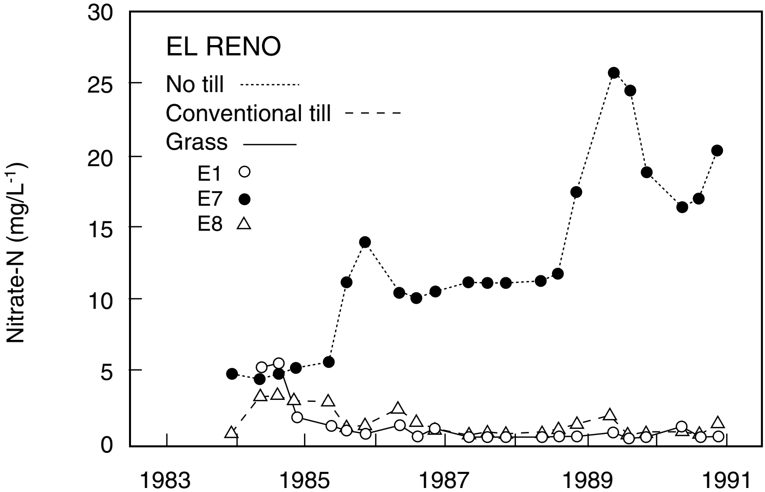


Figure 4.5 Nitrate-N concentrations of groundwater as a function of agricultural management at three water sheds in Oklahoma, USA. E 1 was in native grass from 1977 to 1990. E 7 was in native grass from 1977 to 1978, from 1979–1983 wheat was grown using sweeps and disks to cultivate the soil, from 1984 onwards a no-till system was adopted for wheat production. E 8 was in native grass from 1977 to 1978. From 1979 onwards wheat was grown using sweeps and disks for cultivation. (From Sharpley and Smith, 1994, with permission.)

4.3.4.3 Gaseous Emissions

Gaseous emissions of plant nutrients from the soil are significant only for N. As a result of denitrification, NO_3 is reduced to N_2O and N_2. Apart from that, the application of animal manure or urea fertilizers can add to NH_3 emissions. Nutrient losses via these pathways appear in most cases to be relatively small in terms of overall losses of plant nutrients. N_2O emissions have been estimated to be in the range of 0–10 kg N ha^{-1} a^{-1}.[115,119] Denitrification losses are assumed to be large only under very wet, waterlogged conditions.[11,120] However, these emissions may be causing significant damage to the environment and so must be taken very seriously.

It is widely accepted that denitrification losses tend to be greater in no-till soils than in conventionally tilled soils. This conclusion can be derived from some properties of no-till soils, e.g., higher soil bulk density, higher water content, and consequently a higher probability of anaerobic conditions, larger soil organic matter content, which favors the activity of soil organisms.[11,120] Moreover, laboratory tests analyzing denitrifying activity in soil samples from no-till and conventionally tilled fields suggest that there are differences. These have finally been verified in the field.[121,122]

It is methodologically difficult to measure N_2 emissions in the field because there are high natural N_2 concentrations in the air, but more data exist on N_2O emissions. Laboratory studies have shown that the placement of crop residues impacts denitrification. When residues were placed on the soil surface, denitrification losses were

Table 4.12 Denitrification from No-Till (NT) and Conventional-Till (CT) intact Soil Cores from a Maury Silt Loam Soil

Date	Tillage	Initial Soil NO_3^- (ppm)	Initial Soil Moisture (%)	Irrigation Water (cm)	N_2O Produced (µg N cm^{-2})
June 24, 1980	NT	32	26.8	1.5	7.7
	CT	41	19.1	1.5	0.1**
June 24, 1980	NT	32	26.8	3.1	37.0
	CT	41	19.1	3.1	5.2
July 8, 1980	NT	10	27.2	1.5	21.2
	CT	38	22.2	1.5	2.8*
August 2, 1980	NT	10	21.9	1.5	0.8
	CT	38	15.4	1.5	0.1*
September 6, 1980	NT	4	20.8	3.8	4.1
	CT	6	16.7	3.8	2.7
October 9, 1980	NT	8	22.3	4.1	8.1
	CT	12	16.4	4.1	3.1**
April 27, 1981	NT	98	28.7	4.1	10.5
	CT	83	23.2	4.1	3.7
July 2, 1981	NT	66	27.9	4.1	63.7
	CT	91	20.6	4.1	31.2*

*, **significantly different between tillage treatments with $p < 0.05$ and $p < 0.01$, respectively.

Source: From Rice and Smith 1982, with permission.

larger than when residues were incorporated.[18] Moreover, analysis of the composition of the soil microflora showed that there was a greater potential for anaerobic metabolism in NT soils than in CT soils. Analyzing soil samples of the upper 0–30 cm, Doran showed that populations of denitrifying organisms in NT soils were present at a rate that was two- to threefold of the populations in CT soils.[39] Rice and Smith measured denitrification emissions from intact soil cores that had been sampled from NT and CT plots between June 1980 and July 1981 in an experiment that had been running for 10 years in Kentucky, USA (Table 4.12).[123] The soils from NT plots had lower nitrate concentrations, higher soil moisture content, and greater N_2O production in laboratory assays, after irrigation water was added to the samples. In some cases, denitrifying activity in no-till soils was 77 times greater than in conventionally tilled soils. Significantly more nitrous oxide emissions have been measured in field experiments where nitrous oxide was trapped in sealed chambers above the soil surface.[124,125] On the basis of data from both laboratory and field measurements, attempts have been made to simulate the impact of management practices, including tillage, on nitrous oxide emissions for one site[126] and the whole of the United States.[127] Simulated nitrous oxide emissions in both studies were higher under no-tillage than with plowing. For the agricultural land of the U.S., Mummey et al. calculated overall N_2O-N emissions of 448 Gg ha^{-1} a^{-1} with conventional tillage and 478 Gg ha^{-1} a^{-1} with no-till management.[127]

NH_3 losses must be expected after surface application of urea fertilizers or animal wastes on no-till plots, but these can be controlled by addition of urease inhibitors.[128] Some reduction of volatilization, however, can also be achieved by applying inorganic fertilizers into slots instead of broadcasting them on the soil surface.

4.4 CONCLUSIONS FOR SUSTAINABLE NUTRIENT MANAGEMENT

Soil cultivations for sustainable farming systems should be like soil cultivations in permanent grassland. This means that technical soil cultivation should be minimized and biological soil cultivation by earthworms and other soil organisms enhanced as far as possible. However, since reduced tillage coincides with an increased probability of weed problems, the implications of soil tillage for sustainable nutrient management must be seen in the context of whole farming systems. For example, under the conditions of a temperate climate with moderate rainfall the following differentiations are necessary for conventional, integrated, and organic farming systems.

In conventional farming systems, an extreme reduction of soil tillage is possible. Herbicides can fully replace the weed-controlling effect of soil cultivation in traditional systems. Wherever possible, reduced tillage, including permanent no-tillage, should be used. Consequently, on soils where reduced tillage is feasible and where adequate machinery, pesticides, etc. are available, tillage should be reduced, with the objective of minimizing nutrient losses by runoff and soil erosion and minimizing the risk of nitrate leaching. Higher inorganic fertilizer rates, however, can be necessary during a transition period to account for lower mineralization rates.

Where noninversion tillage is unfeasible, the time and types of tillage should be adjusted to minimize nutrient losses. For example, after growing legume leys or legume crops, as well as after vegetables, oilseed rape, or potatoes, soil tillage should be delayed until the risk of leaching is low and the probability of adequate nutrient uptake by the following crop is high. Under temperate climates conditions with a leaching period over winter this means that tillage should be postponed from autumn to winter or, if possible, until spring.

In integrated farming systems, a compromise over conflict of interests must be managed. According to the IOBC definition, integrated production is "a farming system that produces high quality food and other products by using natural resources and regulating mechanisms to replace polluting inputs and to secure sustainable farming."[129] Under these conditions, the aim of achieving soil conservation competes with the objective of reducing the applications of pesticides. This discrepancy must be resolved on a case-by-case basis, always setting the preservation of natural resources and regulating mechanisms at the top of the list. An arable soil, in particular an arable soil of high fertility, is an important slowly regenerating resource. This means that in many cases reduced tillage must be used to avoid soil losses by wind or water erosion. The concurrent problem of increased weed infestations can be solved partially by adjusting rotations and using indirect means of weed control.

In organic farming systems, the situation is completely different. Plowing is a very effective means of controlling weeds and removing perennial leys. Additionally, the risk of nutrient losses by erosion and surface runoff is significantly less than in conventional or integrated farming systems, as is therefore the need to preserve soil by reduced tillage. Nevertheless, soil conservation has been an issue in organic farming for many years. A combination of shallow-soil inversion and deep-soil loosening is seen as an ideal solution and as a compromise between the need to control weeds by plowing and minimizing the technical impact of cultivations on soil. In organic farming

systems, adjusting the time and types of tillage is an important management tool for sustainable nutrient management. Tillage should be used in a sensible way to keep most nutrients within the system; this means postponing tillage or reducing tillage intensity to times when the risk of nitrate leaching is low.

These three examples show clearly that the implications of tillage for sustainable nutrient management can be judged only in the context of whole farming systems. Conclusions that have been drawn under one particular production system are not necessarily valid under another. This is also true when considering farming systems under a range of climatic and soil conditions. At the same time, however, it should always be remembered that tillage of large areas of land is a man-made process. In natural ecosystems, soil disturbance is usually limited both, with regard to space and frequency of tillage, and plants still thrive without tillage and are sufficiently nourished.

4.5 SUMMARY

This chapter has analyzed the effects of soil tillage on nutrient dynamics. Tillage is analyzed for its short-term and long-term effects. A single tillage operation tends to increase mineralization of soil organic matter and added organic material due to better contact between soil and organic material and due to improved aeration. Long-term, however, a more grassland-like ecosystem can be achieved with reduced tillage or no-tillage, which can be as productive as a system with conventional plowing. Nutrients and soil organic matter are concentrated near the soil surface. The soil organic matter content is increased, thereby allowing net mineralization to be as great as in conventionally plowed soils. Crop growth can be as good as or even better than in conventionally plowed soils, less in temperate climates with sufficient rainfall, but more in areas where water is a major growth-limiting factor. Nutrient losses via surface runoff and soil erosion are less in reduced-tilled systems, and leaching losses tend to be unaffected. However, losses via gaseous emissions, in particular emissions of nitrous oxide, tend to be more in reduced-tilled soils.

Reduced tillage can be part of a sustainable production, but it can be managed only when herbicides and adequate machinery are available; therefore, it is not a feasible system for many areas in the developing world or for production systems with a restriction on chemical weed control, as, for example, in organic farming.

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